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ELECTRON COLLISION FREQUENCY VERSUS CHARGED PARTICLE SEEDING

FEBRUARY 1966

J. Hoffman

Prepared for

DIRECTORATE OF AEROSPACE INSTRUMENTATION

ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

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Project 705.1
THE MITRE CORPORATION
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FOREWORD

The author wishes to thank E. R. Lanczi of The MITRE Corporation for reviewing the manuscript.

REVIEW AND APPROVAL

Publication of this technical report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

C. V. Horrigan

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Acting Director
Aerospace Instrumentation

ABSTRACT

One method of controlling electromagnetic plasma interaction is by seeding the plasma with highly charged particles to obtain relatively large values of the collision frequency. This report contains a description of the maximum obtainable collision frequency as a function of ultrafine charged particle seeding parameters.

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SECTION I
INTRODUCTION

BACKGROUND

The problem of controlling the behavior of a signal as it traverses a plasma has received extensive attention. Proposed solutions include, among others, such diverse methods as increasing the signal frequency, applying a magnetic field, and reducing the electron concentration. This report describes one additional approach: that of charged particle seeding, wherein a plasma is seeded with highly charged particles to change its characteristics in a predictable way.

PLASMA BEHAVIOR

Bases of Investigation

Three aspects are of interest in this area of investigation. First, seeding a plasma with highly charged particles is, in reality, two techniques in one. A number of investigators have already explored electron reduction through the use of charged particles. A further advantage would be gained by investigating the combined effect of both phenomena: electron reduction simultaneous with collision frequency increase, since this is what actually occurs.

Second, in the area of rocket propulsion, an interest in charged particles already exists in relation to colloidal ion engines. It would be advantageous to seek an understanding of this new type of exhaust.

Third, this avenue of investigation provides an opportunity to develop an understanding of the fundamental behavior of a plasma. To date, workers in

the field, including those at MITRE, have created extremely simplified models in order to obtain possible trends for use as guides in more extensive investigations. The approach has been to decouple the various physical phenomena and then base predictions on the extrapolation of existing models.

It is believed that focusing on collision frequency as a dominant mechanism will provide an additional insight into plasma. It is hoped that the brief treatment contained in this report will be the forerunner to a more in-depth analysis.

Collision Mechanisms

It has been established that the deleterious effects of electromagnetic-plasma interaction may be minimized by controlling the electron collision frequency. Increasing the collision frequency to a value greater than the plasma frequency and the signal frequency results in decreased attenuation, phase shift and reflection.

There are two basic collision mechanisms: electron collisions with neutral particles and electron collisions with charged particles. The collision frequency is a function of electron energy, particle concentration, and the effective particle size. The effective particle size for charged particles is a function of the charge squared. Thus, highly charged particles are desired. To obtain highly charged particles, ultrafine particles of micron size are required.

For a specific ultrafine particle of a given radius, there is a maximum obtainable charge. This, in turn, results in a maximum possible collision frequency. The purpose of this report is to establish this maximum collision frequency as a function of the seeding parameters.

SECTION II

COLLISION FREQUENCY

GENERAL

The electron collision frequency can usually be increased by the addition of material per unit volume of plasma (a pressure increase). This increases the concentration of particles with which the electrons collide. For example, doubling the pressure doubles the collision frequency. However, this requires twice the propellant weight for a rocket exhaust plasma. Clearly, then, the approach desired is one which would require only minute seeding to produce large changes in the collision frequency.

The use of charged particle seeding appears to offer this result. Specifically, the required amount of seed material, and the size of the ultrafine particle and its individual charge, will be determined for a given acceptable attenuation loss. The constraint used is that, for a given particle radius, there is a maximum attainable charge.

The m. k. s. system of units is used throughout. Numerical values employed are:

$$\epsilon_0 = 8.854 \times 10^{-12} \frac{\text{coulomb}^2 \cdot \text{seconds}^2}{\text{kilogram} \cdot \text{meter}^3} ,$$

$$e = 1.60 \times 10^{-19} \text{ coulomb} , \quad \text{and}$$

$$m = 9.11 \times 10^{-31} \text{ kilogram} .$$

MAXIMUM OBTAINABLE

The electric field on the surface of a charged ultrafine particle is

$$E = \frac{Ze}{4\pi\epsilon_0 a^2} , \tag{1a}$$

where

E = electric field intensity,

Z = particle charge in units of electron charge,

e = electron charge,

ϵ_0 = dielectric constant of free space, and

a = particle radius.

There is a maximum field strength (in a vacuum) that a surface can stand before destruction of the surface occurs. This then determines the maximum particle charge obtainable. From Equation (1a),

$$Z_m = \frac{4\pi\epsilon_0}{e} E_m a^2 = 6.95 \times 10^{-4} E_m a_u^2 , \tag{1b}$$

where

Z_m = maximum obtainable particle charge,

E_m = maximum permissible surface field, and

a_u = particle radius (microns).

From Reference 1, the electron collision frequency for charged particles is

$$\omega_{c,s} \approx 2 \times 10^{-10} n_s f \frac{Z^2}{T_u^{3/2}} , \tag{1c}$$

where

$\omega_{c,s}$ = charged particle electron collision frequency,

n_s = charged particle concentration,

f = factor accounting for long range coulomb interaction ($1/10 < f < 1$), and

T_u = temperature in thousands.

The maximum obtainable collision frequency $\left(\omega_{c,\,s}\right)_m$, is then

$$\left(\omega_{c,\,s}\right)_m \approx 10^{-16}\, n_s\, f\, E_m^2\, \frac{a_u^4}{T_u^{3/2}} \,. \tag{1d}$$

The volume per particle times n_s is the total volume V_s occupied per cubic meter by the particles. Thus,

$$V_s = \frac{4}{3}\,\pi\, a^3\, n_s = 4.19 \times 10^{-18}\, a_u^3\, n_s \,, \tag{1e}$$

and

$$\left(\omega_{c,\,s}\right)_m \approx 20 f\, E_m^2\, \frac{a_u}{T_u^{3/2}}\, V_s \,. \tag{1f}$$

Reference 2 shows that the experimentally determined maximum surface field strength is approximately 10^{10} volts/meter. Thus,

$$\left(\omega_{c,\,s}\right)_m \approx 10^{20}\, \delta^2\, G\, V_s\, a_u \,, \tag{2a}$$

where

$$E_m = 10^{10}\, \delta \,, \quad \text{and} \tag{2b}$$

$$G = 20\, \frac{f}{T_u^{3/2}} \,. \tag{2c}$$

SEEDING PARAMETERS

For successful transmission through a plasma, the attenuation is (from Reference 1)

$$L \approx 1.5 \times 10^{-8}\, \frac{\omega_p^2}{\omega_c}\, F \,, \tag{3a}$$

where

$$\omega_p^2 = 3.17 \times 10^3 \, n_e \, , \tag{3b}$$

$$F = \frac{1}{1 + \left(\omega/\omega_c\right)^2} \leq 1 \; ; \tag{3c}$$

and where

ω_p = angular plasma frequency,

n_e = electron concentration, and

L = attenuation (decibels/meter).

For charged particle seeding, the reduced attenuation L_s is

$$L_s \approx 5.5 \times 10^{-25} \frac{n_e}{V_s \, a_u} \left(\frac{F}{\delta^2 G}\right) \tag{4a}$$

where Equations (2a), (3b), and (3a) have been used.

In a rocket exhaust, the volume per molecule times the number of molecules n_0 is the total volume V_0 occupied per cubic meter of exhaust plume. Thus, for a molecular radius equal to 3×10^{-10} meters

$$V_0 \approx \frac{4}{3} \pi \left(3 \times 10^{-10}\right)^3 n_0 \, , \tag{4b}$$

and Equation (4a) becomes

$$L_s \approx 5 \times 10^3 \left(\frac{n_e}{n_0}\right) \left(\frac{V_0}{V_s}\right) \left(\frac{1}{a_u}\right) \left(\frac{F}{\delta^2 G}\right) \, . \tag{4c}$$

Equation (4c) is the attenuation per meter as a function of the ionization fraction, charged particle seeding fraction, charged particle size, and the lumped parameter, $F/\delta^2 G$.

These parameters can be examined by way of the alkali-seeded, acetylene-oxygen laboratory flame, discussed in Reference 3. From this reference

$$T \approx 2500^{o}K \ , \quad T_u \approx 2.5 \ ,$$

$$\omega \approx 6.28 \times 10^{10} \text{ and } 2.2 \times 10^{11} \text{ radians/sec} \ ,$$

$$n_0 \approx 2.5 \times 10^{24} \text{ molecules/m}^3 \ , \text{ and}$$

$$\omega_{c,0} \approx 2.5 \times 10^{11} \text{ collisions/sec} \ .$$

Ionization Fraction $\left(n_e/n_0\right)$

From Reference 3, it is known that $\omega_p = 8 \times 10^{10}$ radians/second is a typical laboratory plasma frequency. This implies that $n_e = 2 \times 10^{18}$ electrons/cubic meters. Therefore, the ionization fraction is

$$\frac{n_e}{n_0} \approx 10^{-6} \ . \tag{5a}$$

Attenuation Per Meter (L)

From Reference 3 for $\omega_p = 8 \times 10^{10}$ radians/second, it is shown that

$$L = \begin{cases} 354 \text{ decibels/m for } \omega = 6.28 \times 10^{10} \text{ radians/sec} \\ 219 \text{ decibels/m for } \omega = 2.2 \times 10^{11} \text{ radians/sec} \ . \end{cases} \tag{5b}$$

The seeding parameters required to reduce the attenuation to 1/100 of that shown in (5b) are determined by

$$\frac{L_s}{L} = 10^{-2} \quad . \qquad (5c)$$

Lumped Parameter $(F/\delta^2 G)$

Since $\omega_{c,0} > \omega$ and the intention is for $\omega_{c,s} > \omega_{c,0}$ then, from Equation (3c),

$$F \approx 1 \quad .$$

In Reference 4 it is shown that micron-size particles have been consistently charged to field strengths

$$E \approx 2.5 \times 10^9 \text{ volts/m} \quad .$$

Thus, from Equation (2b),

$$\delta = 1/4 \quad .$$

The long-range coulomb factor f will require experimental determination. For now, an average value can be chosen:

$$f = 1/2 \quad .$$

Thus, from Equation (2c),

$$G \approx 2.5 \quad .$$

The lumped parameter is then

$$\frac{F}{\delta^2 G} \approx 6 \quad . \qquad (5d)$$

Charged Particle Seeding Fraction $\left(V_s/V_0\right)$

Substitution of Equations (5a) through (5d) into Equation (4c) yields

$$\frac{V_s}{V_0} \approx 8 \times 10^{-3} \left(\frac{1}{a_u}\right) , \tag{6a}$$

where the approximation includes both values in (5b). Since

$$m_0 = \rho_0 V_0 , \tag{6b}$$

and

$$m_s = \rho_s V_s , \tag{6c}$$

then

$$\frac{m_s}{m_0} \approx 8 \times 10^{-3} \left(\frac{1}{a_u}\right) \left(\frac{\rho_s}{\rho_0}\right) , \tag{6d}$$

where

m_0 = mass of unit volume of exhaust gas ,

ρ_0 = density of exhaust material ,

m_s = mass of seed material per unit volume , and

ρ_s = density of seed material .

If

$$\rho_s \approx \rho_0 ,$$

and

$$a_u \approx 2 \text{ microns} ,$$

then

$$\frac{m_s}{m_0} = \frac{V_s}{V_0} \approx 4 \times 10^{-3} \quad . \tag{6e}$$

Thus, seeding with four parts per thousand by weight reduced the attenuation by 1/100.

Finally, the required charge per particle, the charged particle concentration, and the resulting collision frequency can be determined. From Equations (1b) and (2b),

$$Z_m = 6.95 \times 10^{-4} \left(\frac{1}{4}\right) \times 10^{10} \, (2)^2 \approx 7 \times 10^6 \; ; \tag{7a}$$

from Equation (4b),

$$V_0 \approx 3 \times 10^{-4} \; \frac{\text{meter}^3}{\text{cubic meter}} \; ; \tag{7b}$$

and from (6e),

$$V_s \approx 10^{-6} \; \frac{\text{meter}^3}{\text{cubic meter}} \; . \tag{7c}$$

Thus, from Equation (1e),

$$n_s \approx 10^{10} \text{ charged particles/meter}^3 \; , \tag{7d}$$

and

$$\frac{n_s}{n_0} \approx 10^{-14} \; . \tag{7e}$$

From Equations (2a) through (2c), it is known that

$$\left(\omega_{c,\,s}\right)_m \approx 3 \times 10^{13} \text{ collision/sec} \ , \tag{7f}$$

and

$$\frac{\omega_{c,\,s}}{\omega_{c,\,0}} \approx 10^{2} \ . \tag{7g}$$

SECTION III
CONCLUSIONS

The results indicated in this report are very encouraging. For an example of a rather severe case of attentuation, seeding the plasma with charged particles, four parts per thousand by weight, reduced the attenuation by 1/100.

However, it should be kept in mind that these results are based upon a rather simplified charged-particle model. Refinements of this model must include the way the particle receives its charge and the method of seeding the plasma. In addition, the theoretical model should receive experimental results as an on-going refinement process.

Extrapolation of existing models enables large increases in collision frequency to be predicted as a result of seeding with small amounts of highly charged particles. If elastic collisions are assumed, we are able to speculate on the reduction in attenuation and the associated seeding requirements. In general, however, the collisions will not be elastic. Rather, the highly positively charged particles will attract electrons. This will occur at an extremely high rate, as indicated by the large value associated with the collision frequency. This then leads to an even greater potential for the control of electromagnetic-plasma interaction, or, by increasing the collision frequency, a simultaneous reduction of electron concentration occurs to produce the two-pronged effect mentioned previously. Accordingly, the appropriate model must therefore include both effects.

This then leads to the basic question: How does a plasma behave when it consists of highly charged particles? The term "plasma" is used in its

broadest sense. It would appear that an investigation of a highly charged particle plasma is of interest, not only in the area of electromagnetic-plasma interaction, but also from the viewpoint of obtaining a basic understanding of another facet of plasma phenomena.

It is most likely that as work progresses in the area of colloidal ionic propulsion, as well as in other areas, experimental observation will be available to assist in the construction of the pertinent models for analysis and prediction.

It may well be that as one begins to explore the highly charged particle plasma, new areas of interest will be discovered.

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